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Heavy-Ion Physics at LHC

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Abstract. The new conditions which will be reached when LHC will collide lead ions are discussed together with the probes which will become available for studying the properties of the hottest matter ever formed in the laboratory. The experimental requirements and how the LHC experiments, in particular ALICE, will face the challenges are presented.

1. Introduction

Before the first data will be available from the LHC, which is expected to come into operation in 2007, it will remain impossible to predict what the properties of the matter formed in heavy ion collisions will be at such unprecedented high energies. Will matter have the properties of weakly interacting plasma of gluons and quarks carrying the small Chiral mass and thus provide the unique opportunity to study the true vacuum of QCD? Will matter instead be the same perfect partonic fluid or strongly interacting quark and gluon plasma which has been discovered at RHIC energies? Will the new state of matter characterized by a saturated gluon density and dubbed as the Color Glass Condensate play an essential role as the precursor state for the formation of hot nuclear matter? Will there be yet a new state of matter discovered at LHC? Nobody is really in a position today to make firm predictions. Therefore, experiments must be prepared for the unexpected and cannot afford to neglect any observable. The ALICE experiment has been conceived within this spirit and tries to be as complete as possible exploiting all presently known techniques to detect and identify all kinds of particles, which can be produced in nuclear interactions, over a very broad momentum range.

2. From SPS to LHC

Let us briefly review the recent history of the exploration of the properties of hot nuclear matter or the “search of the quark gluon plasma”. In February 2000, CERN announced that a “new State of matter” had been created [1]. Compelling evidence for this new state of matter was provided by the results collected over about 10 years by seven experiments dedicated to measuring a number of crucial observables. The large energy densities reached in Pb-Pb collisions at $\sqrt{s_{NN}}=17.3$ GeV exceeded substantially the critical energy density at which the transition from normal hadronic matter toward deconfined partonic matter is predicted by theory. The measured strangeness enhancement and suppressed charmonia bound state production, as well as hints for thermal electromagnetic radiation, constituted a set of prominent evidences. However the interpretation in terms of the formation of quark gluon plasma was not unique enough to establish unambiguously the properties of the new state of matter.

Four years later, following a very successful start of the RHIC operation, the announcement was made that a strongly coupled QGP has been discovered at RHIC [2]. The claim for discovery has

however not been made by the four RHIC experiments because the smoking gun of the QGP formation has not yet been observed. There is nevertheless a solid line of empirical evidence [3] for the observation of deconfined matter. In Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV, matter is now formed largely exceeding the critical value. An unexpected large elliptic flow, reaching the saturation limit predicted by the hydrodynamic model, has been observed for all measured particle species and has been interpreted in terms of formation of an early collective system at the partonic level. Jets have been found to be measurable through the measurement of leading hadrons and hadron correlations and the results indicate that jet properties are modified by the medium traversed by hard scattered partons. It has been further demonstrated, through observation that similar modifications are absent in d-Au collisions, that the modifications are due to final state effects on the hard scattered partons traversing a color dense opaque medium. A consistent interpretation of the data is given in terms of the formation of a strongly coupled QGP rather than the nearly ideal gas predicted by the theory.

With the advent of LHC and the huge step in energy to reach the nominal $\sqrt{s_{NN}}=5500$ GeV, the study of heavy-ion collisions will enter a new and unexplored regime. Quantitatively matter is predicted to be formed at energy densities and temperatures largely exceeding (by a factor up to 4 for the temperature) the critical values at which QCD calculation on the lattice predict the deconfinement transition to occur and the Chiral symmetry to be restored. In this regime the coupling constant could be sufficiently reduced to approach the state of a weakly interacting gas of the QCD vacuum quanta. The system is expected to be thermalized within a tenth of an fm/c and to remain much longer in the deconfined phase (more than ten fm/c) enhancing the production of rare probes. At the LHC energies the collisions will also enter a qualitatively new regime of partons kinematics. The particle production from very forward to central rapidity will be dominated by hard processes involving partons with small Bjorken- x values, from, for example, $x=10^{-2}$ for $Q=100$ GeV transferred momentum at central rapidity to, $x=10^{-5}$ for the production of J/ψ ($Q=10$ GeV) at very forward rapidity ($y=4$). The saturation regime will therefore determine the property of the initial stage of the collision and the QGP formed at LHC might evolve from a Color Glass Condensate [4]. Hard processes, where the transferred momentum is much larger than the QCD scale or the thermal scale ($Q \gg \Lambda_{QCD}, T$), will contribute significantly (98%) to the total cross section. Particles produced in hard processes are thus expected to be abundant at LHC energies, providing a new and unique set of observables probing the medium at very early times.

3. Hard probes at LHC

They are produced in the early stage of the collision, because of their large virtuality the formation time is short allowing them to be decoupled from the medium, and their production cross section is calculable by perturbative QCD. Hard scattered partons appearing in the detector as a jet of hadrons, heavy flavor quarks and quarkonia, and weakly interacting probes such as photons or W/Z bosons belong to this category of probes.

The properties of partons created in hard scattering in the very early phase of the collision will be modified by the traversed medium. These modifications will be imprinted in the final hadronic state (or jet) of the parton and therefore provide a unique probe of the medium formed during the collision at an early stage. In the vacuum, a parton produced in some hard process with a high virtuality E_T , will lose its virtuality by parton splitting until it reaches the hadronic scale Q (~ 1 GeV). At this scale, the perturbative approximation ceases to apply and the partonic shower fragments into hadrons. The typical length of this hadronisation scales linearly with E_T , $L_{hadr} \sim E_T/Q_{hadr}^2$. The medium will modify these vacuum dynamics. While traversing the medium, high energy partons will more effectively lose the virtuality by gluon radiation. The total radiated energy depends on the properties of the medium which are characterized by a transport coefficient (energy loss by unit of distance) [5], q , and scales with the square root of E_T , $L_{therm} \sim \sqrt{E_T/q}$. The competition between full thermalization (all the parton energy E_T is radiated) and hadronisation depends on the initial energy of the parton and consequently on the observed final-state hadron energy, p_T .

For sufficiently low parton energies so that $L_{therm} < L_{hadr} < L_{medium}$ (i.e., $p_T \leq 2$ GeV/c), the hard parton is thermalized in the heat bath and contributes to the bulk properties of the medium. This sets the ability to detect hadrons down to low p_T (~ 100 MeV/c) as a first experimental requirement. The bulk properties of the LHC medium will most likely follow a monotonic extrapolation from the properties of the RHIC medium. However, one has to be prepared for changes due, for example, to the difference in the expansion dynamics and in the thermodynamics by the inclusion of heavy quarks.

For parton energies for which all the scales are equivalent ($L_{therm} \sim L_{hadr} \sim L_{medium}$), or equivalently for hadrons with $p_T \sim 2$ -10 GeV/c, the hadronisation of the hard parton shower will occur inside the medium, so that the medium can be used as a control parameter to modify the non-perturbative hadronisation process. Thus one can expect to gain some insight into the dynamics of this process and learn about the nature of the pre-hadronic states. Medium modified fragmentation functions have indeed been observed at RHIC [6] in the measurement of proton to pion ratio enhanced by about a factor 10 with respect to the same ratio measured in e^+e^- annihilations and with the ratio expected from perturbative calculations applying the factorization theorem. This sets the next experimental requirement, the necessity of excellent particle identification in a p_T range extending at least up to 10 GeV/c.

For more energetic partons satisfying $L_{therm} > L_{hadr} > L_{medium}$ (i.e., $p_T > 10$ GeV/c), the hadronisation occurs in the vacuum, and the final hadronic state will carry information on the energy lost by the parton inside the medium. Thus, measuring the jet properties under these conditions will enable to derive information on the properties of the medium. The most straightforward measurement will be, as demonstrated by RHIC data, to probe the reduced energy of the initial parton with the reduced energy of the leading hadron. Hadron angular correlations measuring the shape of back to back correlations provide another tool to study medium induced modification of jet properties. Measuring high p_T hadrons with high momentum resolution over a broad range of momenta is the experimental requirement to perform such studies. This kind of measurement is however not very sensitive to the medium properties because the parton energy loss scales like qL^2 [7], where L is the length of the traversed medium, rendering the interior of the medium opaque to these probes.

A better probe will be the modification of the jet topology [7], by measuring the hadron multiplicity in the jet or the heating of the jet (transverse momentum distribution of the hadrons with respect to the jet axis). These observables will be more sensitive to the medium properties as they scale as qL , linearly with the distance traveled inside the medium. For these jet topology measurements one will take advantage of the copious production of energetic jets at LHC. Leading order perturbative QCD calculation predicts that one 10 GeV jet is produced in every Pb-Pb collision and up to 10^4 jets of 200 GeV transverse energy will be produced in one LHC heavy-ion run (effective running 10^6 seconds) at the nominal luminosity of $5 \cdot 10^{26} \text{ cm}^{-2}\text{s}^{-1}$. These jets can be identified together with their topology, provided sufficiently high quality charged hadron and/or electromagnetic calorimetry measurements are available [8]. Because of the high production rate, the quality of jet measurement will be greatly improved by photon tagging. High resolution photon measurements and high quality photon identification are necessary experimental requirements.

At LHC, jet quenching measurements can be extended to heavy quarks to provide an additional constraint to the determination of the transport coefficient. Indeed heavy quarks lose energy less efficiently through medium induced gluon radiation than light quarks do. The measurement of heavy to light quark double nuclear modification ratio will thus be sensitive to the mass and color-charge dependence of medium induced energy loss [7]. The identification of heavy flavor D or B mesons will require, in addition to high quality particle tracking and particle identification (for detection in the hadronic channel), high resolution vertexing as well as tracking and identification of high momentum electrons (for detection in the semi-electronic channel).

4. Heavy-ion experiments

Among the three experiments at LHC, ALICE, ATLAS and CMS, which have an approved heavy-ion program, ALICE is the dedicated heavy-ion experiment. It implements all the requirements which have been mentioned in the previous section. The challenge is to do in one experiment what is being done in four at RHIC. Since predictions for particle density span a broad range of values, ALICE has been optimized for charged particle densities of the order of $dN_{ch}/d\eta = 4000$, but can provide acceptable performances up to values as high as 8000. All known techniques for particle detection and identification are exploited in the design of the ALICE detectors, allowing to measure the flavor (hadrons, leptons and photons) content and the phase space distribution of heavy-ion events on an event by event basis. ALICE is equipped for jet physics which is going to dominate the LHC heavy-ion program. On the low p_T side, up to several tens of GeV/c, jets will be mostly characterized through hadron correlations and leading particle measurements. Jets with p_T around 100 GeV/c and above will be identified allowing detailed study of their topology. Fragmentation functions will be measured down to low fractional momenta for identified charged and neutral particles. ALICE is however still missing (only because of financial constraints) an electromagnetic calorimeter with large acceptance, which would greatly extend the jet physics reach of ALICE.

5. Conclusion

In 2007, the LHC experiments will be ready to take data. First pp beams are scheduled to collide, with reduced luminosity, by mid 2007. A first heavy-ion pilot run may take place already in 2007. The first full heavy-ion run is scheduled to take place in 2008, with reduced luminosity. Within the first 15 minutes at nominal luminosity, data could be collected with sufficient statistics to measure the particle multiplicity, the low energy particle spectra, and the particle production ratios. Within one month of data collection, the statistics would be sufficient to study rare high p_T processes such as jets, D and B mesons, quarkonia and direct photons. The following runs could then be devoted to the same measurements in pA collisions, and to heavy-ion mass and energy scans. Until then, the collaborations continue to invest a huge amount of effort to guarantee a timely completion of the detectors and the accelerator.

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